# Remote assessment of tsunami damage in Japan by means of Google Street View images

## Project Report

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**Abstract**

The devastating Great East Japan tsunami of 2011 highlighted the vulnerability of urban habitations to such major disasters and the need to improve survivability. As has become the norm after such events, field teams were sent to investigate and learn lessons to aid future design guidelines.

In addition, Google Street View cars were sent around inundated areas once roads were cleared and the resulting images were displayed online allowing ready comparison with images taken before the event. This report is the output from a project which examined this remote assessment tool to determine its usefulness for engineers. It was found that much of what is observable in the field is also visible in the online archive. Performance of structures of different types can be assessed both quantitatively, as a function of distance from the shoreline, and also qualitatively for beneficial features such as open ground floors. Advantageous features of urban design such as sheltering by trees and other buildings, and siting of structures to serve as vertical evacuation centres could, also be assessed.

Overall, although the online images cannot completely replace a field survey, they have the potential to exploit untapped resource in researchers around the world collaborating with local engineers to learn lessons and improve tsunami resistance of vulnerable coastal communities.

## Introduction

Tsunamis can have devastating impact on inhabited coastal zones, causing inundation and widespread destruction up to 5km inland depending on the land's topography, as experienced in the Great East Japan (Tohuko) event of March 2011. Because of the high tsunami wave speed in open water, it is difficult to provide adequate warning to evacuate coastal areas. There is a need to improve both the performance of individual structures (with an emphasis on survivability) and the configuration of urban areas as a whole, to mitigate the wave impact.

The most recent tsunami design code for ordinary onshore structures is the FEMA P55 Coastal Construction Manual (FEMA, 2005). Design methods may be developed through physical modelling in a wave tank (*e.g*. Collins *et al*., 2012); however it is hard to reproduce the hydraulic conditions, their impact on structures and the structural response all in one laboratory test, due to scaling difficulties. Field investigations, as carried out for the Indian Ocean (2004), Chile (2010) and Tohoku (2011) events (EEFIT, 2006, 2010 & 2011), have therefore been important to developing understanding of tsunami engineering.

Such investigations are normally carried out soon after the event, with data collection on performance of individual structures (related to their form, material, age and location), measurements of inundation height, interviews with local residents, *etc*. Research into the 2004 Indian Ocean Tsunami was carried out by Tohoku University International Research Institute of Disaster Science (IRIDeS) within the first month following the disaster (Kawata *et al*., 2005). To witness the undisturbed debris field, field teams need to reach the area within the first two weeks, however this early arrival may obstruct emergency relief operations.

In Tohoku (2011), the Ministry of Land, Infrastructure and Transportation of Japan (MLIT) carried out a comprehensive survey of over 250,000 structures in seven provinces affected by the disaster (Suppasri *et al*., 2013). The Earthquake Engineering Field Investigation Team (EEFIT) of the UK returned two years later to examine the recovery and reconstruction process (EEFIT, 2013). Further field studies are reported by EEFIT (2013, ps. 21, 28).

Advances in technology have made remote data collection possible as an alternative to field investigations. After Chile (2010), GPS and high-resolution pre- and post-event satellite imagery were used to collect data prior to the EEFIT field investigation, including inundation and debris extents, changes in shoreline and even damage status of individual buildings, helping it to focus on more heavily damaged areas.

For the first time, after Tohoku (2011), pre- and post-event imagery has been made available together in one online portal via Google Street View (2011) (GSV), enabling web users to zoom in on individual streets and buildings. Data on inundation height and damage to individual buildings could potentially be obtained from such imagery whilst offering the following advantages over field investigations:

- A more accurate overall view of damage caused by a disaster, rather than sampling at a limited number of sites.
- Allowing communities to rebuild without unnecessary interference during relief operations, except for the need to allow access for the GSV car.
- Permitting opportunity for reflection and for re-examination of the data, without the time limitation of a field study.

The ability of remote GSV data to ascertain the age, structural form, materials and scale of damage within individual buildings may be limited, making field investigations still necessary to conduct interviews or examine buildings close at hand. This study aims to investigate what can be learnt from the GSV Tohoku pre- and post-event images and to evaluate to what extent such a remote assessment methodology could replace or augment a traditional field investigation. The focus will be on two aspects – performance and design of individual structures, and understanding of how building configuration and location relative to shoreline affects damage distribution. The latter includes consideration of Vertical Evacuation Shelters – positioning and potential provision from buildings constructed for another purpose. Technical conclusions of the study are compared with those of the other major field-based studies, chiefly EEFIT (2011).

**Background to the remote data collection**

Google Street View cars were sent around major cities and coastal areas of Tohoku, photographing streets over a six month period starting four months after the tsunami. Images were compiled with those taken before the event to produce an accessible digital archive laid out to allow straightforward comparison of the 'Before' and 'After' situations at any location. Figure 1 shows a typical screenshot.

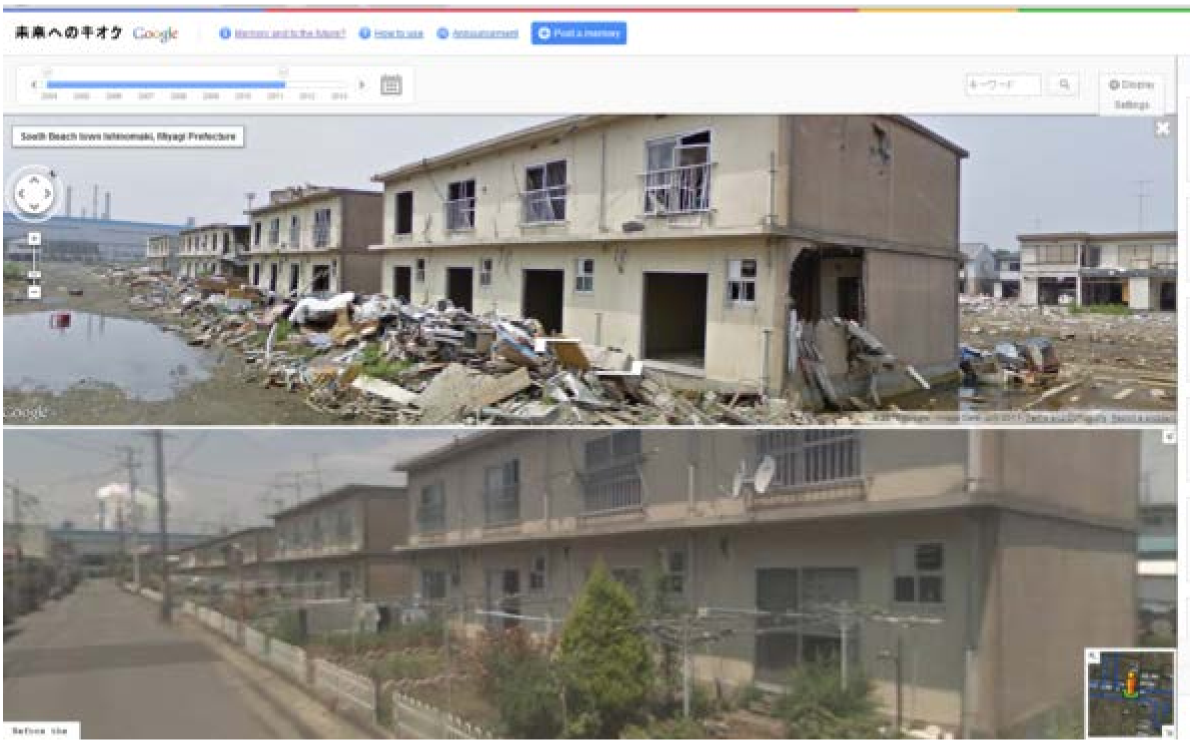


**Figure 1** 'Before' and 'After' Google Street View image (Google Street View, 2013a)

The coastline of northeast Japan is of two main types: coastal plains and ria coasts (Fig. 2). The former comprise extensive areas of flat, low-lying land adjacent to the ocean. In contrast, ria coasts have limited flat land but are characterized by narrow, funnel-shaped coastal inlets or ‘rias’, bounded by mountains. Tsunami inundation has different characteristics in these two areas, with the ria coasts sharply concentrating the tsunami wave, increasing its amplitude and energy at the shoreline, whereas coastal plains do not accentuate the wave height but allow it to penetrate further inland. Thus coastal type strongly influences both extent and severity of damage to an urban area, and hence how it should be planned and constructed.

For this study, one coastal plain area (Ishinomaki) and one ria coast district (Ofunato) were surveyed (Fig. 2), both partially inundated and both visited by EEFIT (2011). GSV data was available for the entire inundated areas, although for this study sample zones were examined. Buildings completely obliterated could not be surveyed – only those left standing. The aim was to collect data on at least 100 such buildings in each settlement.

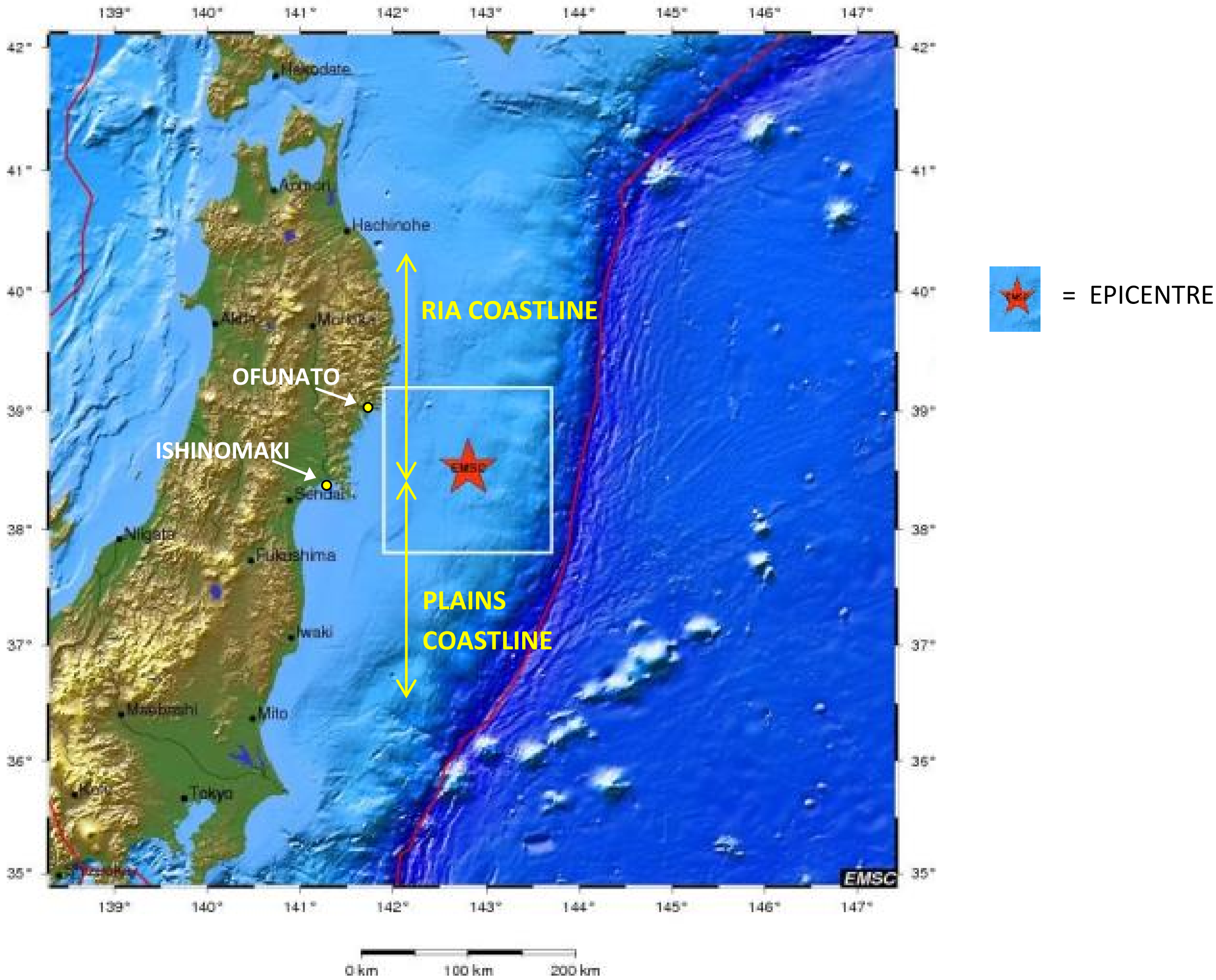



**Figure 2** Tohoku coastline, showing ria and coastal plains extents and surveyed districts, Ofunato and Ishinomaki (EMSC, 2012)

Residential buildings in Japan are usually either single-family detached dwellings or apartment blocks. 88% are constructed of timber (Ministry of Internal Affairs and Communications 2008, Ch.21-9), which was likely to be true in the surveyed areas with smaller numbers of other forms such as reinforced concrete (RC) and steel frames also present (particularly for larger structures). To compare performance across these different forms, a damage grading scale was used, with four categories focussing on survivability, habitability and reparability:

D1. Survivable – would a person in the building survive the force of the tsunami?

D2. Habitable – can it be occupied in the immediate aftermath?

D3. Repairable – would it be possible to repair the building, making it habitable (focussing on technical feasibility, not economic viability)

D4. Collapsed – although standing sufficiently to allow identification, the building is not repairable and must be replaced.

Examples of the damage categories for buildings of each of the main structural types encountered in the study are shown in Table 1. The damage category is judged by viewing the building from as many directions as possible in GSV. Each building is given a unique reference number and its co-ordinates logged for later analysis. To understand its damage in the wider context, the following information was also gathered:

- Distance from shore (m)
- Building usage, *e.g*. industrial, commercial, residential
- Building frame and cladding materials
- Location in relation to other buildings – to assess if effects of sheltering are evident

The total number of buildings present in each zone before the tsunami was estimated from the 'Before' GSV images, and hence the proportion left standing afterwards calculated. Both quantitative and qualitative analyses were carried out on data from each zone, with quantitative data presented in the form of stacked bar charts, examining the performance of structures of different frame types at varying distances from the shoreline, and qualitative data presented as case studies of building design and configuration that appearing to perform well relative to distance from the shoreline.

**Case Study 1: Ofunato**

Ofunato is a city on the ria coastline, located in a narrow bay bounded by steep hills. Despite the wave funnelling to an inundation height of 13.13m at the shoreline, the steep rise in topography meant that 69% of housing escaped inundation (EEFIT, 2011). The harbour front is occupied by commercial buildings. Sample zones were chosen either side of the bay (Fig. 3) containing a total of 696 buildings before the tsunami, of which 108 (15.5%) remained standing sufficiently to be surveyed.

Table 1 Damage features representative of damage categories D1-D4 (Google Street View, 2013c)

| | Timber | Light Gauge Steel | Structural Steel | Reinforced Concrete |
|---|---|---|---|---|
| D1 |  (a) - B49 - Ishinomaki |  (b) - B43 - Ishinomaki |  (c) - A65 - Ishinomaki |  (d) - A3 - Ishinomaki |
| D2 |  (e) - A66 - Ishinomaki |  (f) – B40 - Ishinomaki |  (g) - A26 - Ishinomaki |  (h) - A14- Ofunato |
| D3 |  (i) - A29 - Ishinomaki | NO IMAGE AVAILABLE |  (j) - A31 - Ishinomaki |  (k) - A24 - Ofunato |
| D4 |  (l) - A8 - Ishinomaki |  (m) - A20 - Ishinomaki |  (n) - A70 - Ishinomaki | NO D4 RC BUILDINGS SURVEYED |

**Figure 3** Sample zones at Ofunato 'Before' and 'After'- 04/04/10 (Google Earth 7.0, 2010a) (left) and 03/04/12 (Google Earth 7.0, 2012a) (right)

Quantitative Data Analysis

Data for the three sample zones were aggregated for analysis as they showed similar building distributions. Figure 4 shows that timber buildings were most heavily affected, with 36% of those left standing suffering D3 or D4 damage, followed by RC (25%), followed by steel (11%). More data on light steel framed buildings is available from Ishinomaki.

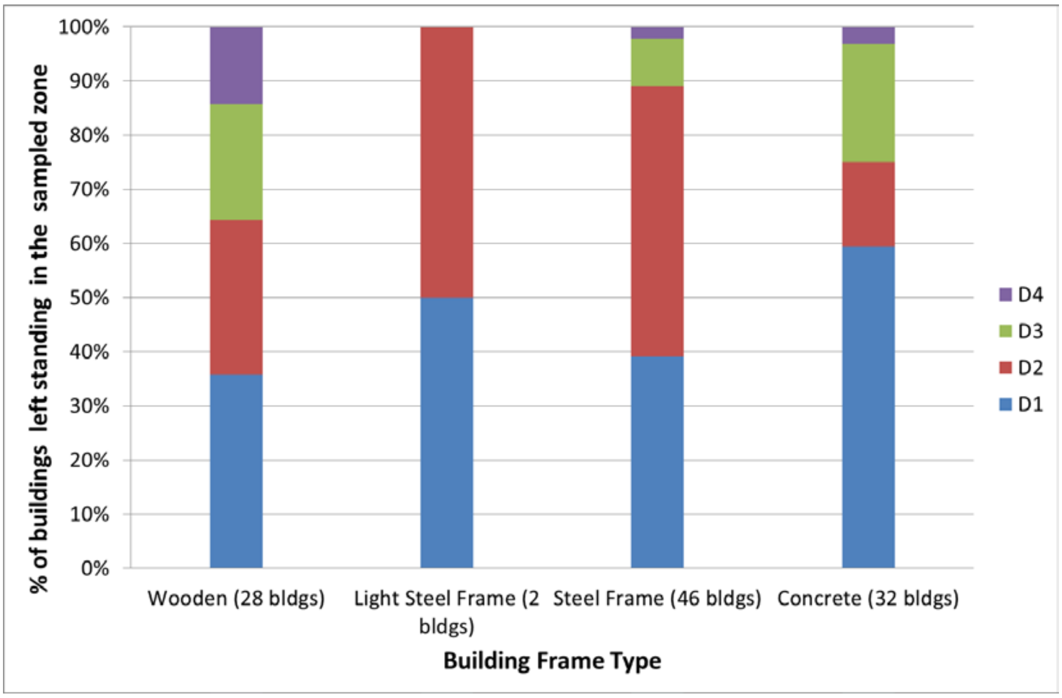



**Figure 4** Damage levels by building frame type for Ofunato (aggregated for all sample zones)

Figure 5 shows damage level with distance from shoreline, for all structure types. Only beyond 500m from the shoreline did the proportion of D3 and D4 buildings decrease (although the number of buildings is small at that distance). In the first 500m there is no clear damage trend, even though as the wave travels inland its speed and energy would be expected to decrease. A possible explanation is that accumulation of debris at the wave front, as noted by eye-witnesses, contributed to damage as the wave moved inland.

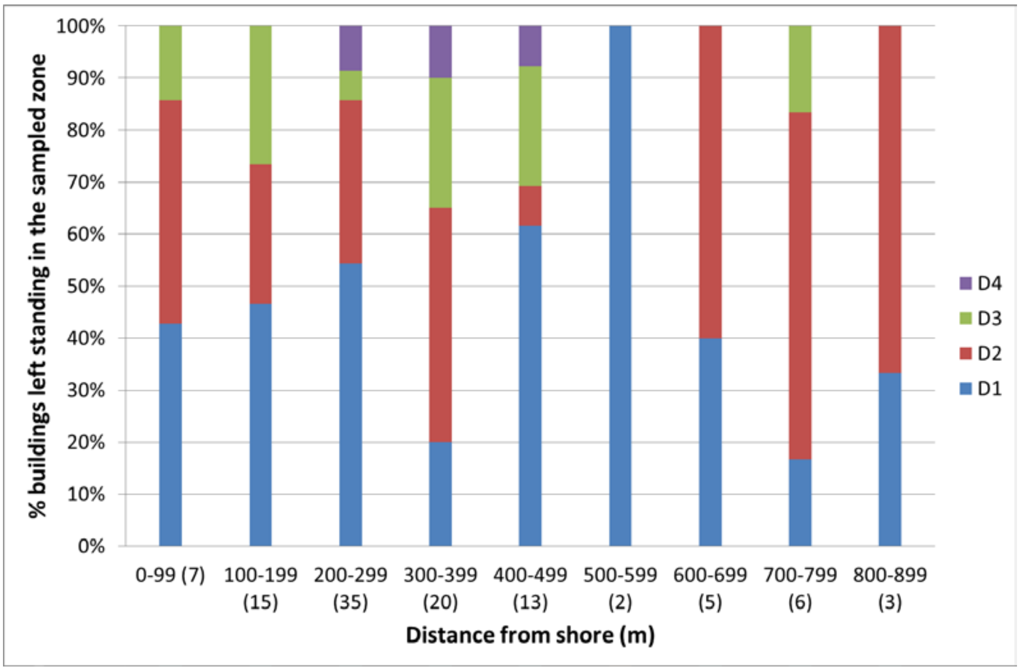



Figure 5 Damage levels with distance from shoreline – Ofunato (aggregated for all sample zones and building types, number of buildings at each distance in brackets)

Repair and Rebuild Operations

Although 84% of buildings were obliterated and could not be analysed, damage levels for those remaining were lower than might be expected, for example only 36% of surveyed timber buildings suffered D3 or D4 damage. It was evident from GSV that six months after the tsunami, Ofunato had been extensively cleared up and was now under repair and rebuilding, with little debris on the ground and a high proportion of surveyed buildings under scaffold. Many wooden houses were relatively undamaged and had evidence of new windows and other repairs. It is possible that the most heavily damaged buildings had already been cleared, explaining the low damage statistics of those remaining.

Building Design Features

72% of buildings left standing at Ofunato were of strong frame type (steel or RC), predominately larger commercial or residential apartment buildings. Of these, 75% of the steel and 89% of the RC buildings had relatively light damage (D1/D2). A common feature of commercial buildings (although less so for the apartment blocks) was an open plan ground floor. Generally it appears that larger engineered buildings are a realistic design solution for areas of potential inundation.

**Case Study 2: Ishinomaki**

Ishinomaki is a port town on the coastal plains, with an estimated population of 117,233 (see http://www.geonames.org/maps/cities.html). Most of the city's commercial and industrial buildings are located around the port, with residential areas generally further inland. 69% of the city's population was situated in the inundation zone (EEFIT, 2011).

Data were collected in two sample zones either side of the River Kitakami (Fig. 6). 'After' images were taken in July 2011, four months after the event.


**Figure 6** Ishinomaki survey sample zones, 'Before' – 04/04/2010 (Google Earth, 7.0, 2010b)

Quantitative Data Analysis

Figure 7 shows the sample zones in more detail after the tsunami. Although both contained mainly residential and small commercial buildings, their situation relative to the shoreline is different, with Area A in close proximity but Area B set back about 400m behind the port. Area A experienced approximately 91% obliteration of buildings compared to 68% in Area B. This is likely to be due to shielding by the port area that was densely filled with large industrial steel framed buildings, many of which remained standing to some extent.


**Figure 7** Ishinomaki: Area A 'After' - 03/04/12 (Google Earth, 7.0, 2012b) (left), Area B 'After' - 03/04/12 (Google Earth, 7.0, 2012c) (right)

From the relationship between structure type and damage categories (Fig. 8) it can be seen that as the strength of the building frame increases (from timber to light steel to RC), damage severities decrease. Light steel performed better than timber. There is an unexpected trend of greater damage to steel-framed buildings, where it was noted that 61% of surveyed buildings suffered partial or complete loss of cladding and subsequent damage to the non-structural components of the building. 42% of steel buildings were commercial/industrial with light panel cladding, which proved to be insufficiently robust against the tsunami impact.

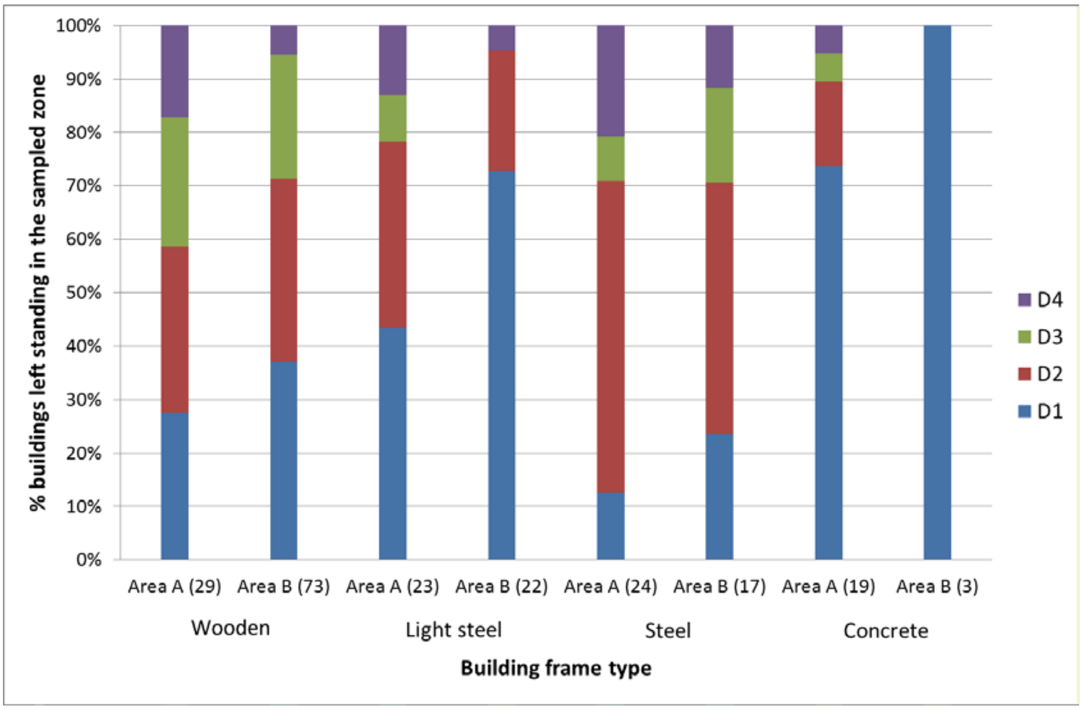



**Figure 8** Damage levels by building frame type for Ishinomaki (Areas A and B) (number of buildings of each type in brackets)

Thus, although lighter construction forms such as timber and light steel do not survive well under tsunami impact, the noticeably better outcome in Area B (Fig. 9) suggests that positioning major infrastructure and larger structures on the shoreline can significantly improve performance in zones inland.

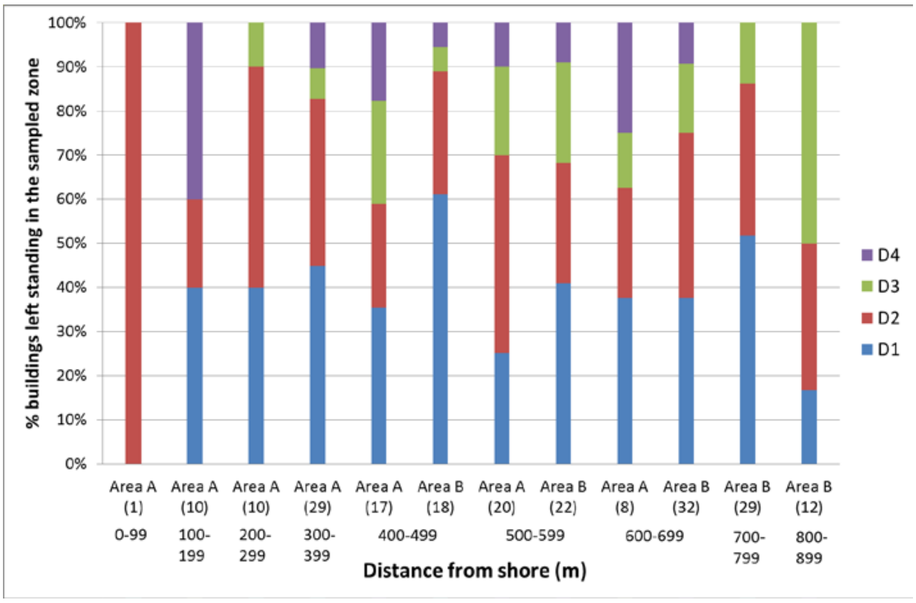



**Figure 9** Damage levels with distance from shoreline – Ishinomaki (Areas A and B)

Building Design Features

***Open Ground Floor Construction*** was seen in a number of residential and commercial buildings. This enabled water to pass through with minimal resistance and the building frame to stay intact (*e.g.* Table 1(c), Figures 14 and 15). Sufficient bending and shear strength is required in the ground floor columns to resist the wave impact.

***Dual Frame Construction*** is a noticeable design feature of housing in Ishinomaki, where a number of buildings remained standing with an RC or steel-framed ground floor and timber-framed construction for the upper floors (Fig. 10). The ground floor was often used as a garage, or sometimes commercial space in a mixed-use structure. In Ishinomaki, the inundation height was equivalent to two storeys and in the majority of cases observed, the RC/steel ground floor survived virtually undamaged, while the timber upper floors were heavily damaged or washed away (suggesting insufficient strength or connection to the ground floor frame). These buildings performed better overall than pure timber frames that were either completely destroyed or suffered collapse of the ground floor. This was also noted by EEFIT (2011, p101), referring to them as 'raised dwellings'.

**Figure 10** Dual frame construction building A25 in Ishinomaki 'Before' (GSV, 2013d) (left) and 'After' (GSV, 2013c) (right)

***Structural concrete panel construction***. Within the 9% of buildings left standing in Area A was a group of seven two-storey apartment blocks of concrete structural panel type (Fig. 1) (EEFIT (2011) describe similar buildings as 'RC shear wall construction'). They survived with damage levels D1 to D3 (four of the seven at D1), despite being inundated to roof level and with almost everything else around them washed away. This could potentially be a very important form of construction in coastal communities, if constructed higher than inundation level to improve survivability. Damage was worst at the corners where the waves were funnelled around the buildings. This was also observed in other structures, suggesting buildings should be orientated longest side perpendicular to the shoreline to reduce flow speeds around corners, and corners of buildings designed for greater wave forces.

***Sheltering by trees***. A group of small commercial and residential structures of light frame construction (probably timber) were identified with damage rating D1, 435m from the shoreline in Area B (Fig. 11). Behind and to the right when viewed from the shore, very few buildings were left standing or not heavily damaged. The only clear reason for this group of buildings' survival is sheltering from a line of trees still standing directly in front of them, between the residential area and the port. These trees relied in turn on a degree of sheltering from the port area buildings, as trees at other locations along the shorefront were uplifted from their roots and did not survive the tsunami.

**Figure 11** Buildings in Area B behind the port in Ishinomaki showing evidence of sheltering by trees (GSV, 2013c)

### Lessons for urban planning and zonal redevelopments

The majority of reports on tsunami effects focus on performance of individual structures. However, it should be possible to observe how communities as a whole fared and if urban planning can reduce the impact of tsunamis. Of the five post-tsunami investigation teams IRIDes appointed, only one, in the Maldives, looked at redevelopment to improve the overall safety level of an area (Kawata *et al*., 2005, Ch.5, p.77). To do so requires research into the relationship between damage and distance from the shore, the effects of sheltering from neighbouring buildings, topography of the land and inundation extents, to which a study using GSV can contribute.

Coastal plains experience a tsunami wave of lower inundation height and force than ria coasts, but a large area is affected. This makes it hard to protect residential areas just by relocation to higher ground. Measures are required to dissipate the wave, slowing it down and reducing its impact. Ishinomaki showed this can be achieved by locating larger industrial and commercial structures along the shoreline, followed by lines of trees in front of, and possibly within, the residential areas. Residential buildings should be constructed higher than inundation level, ideally three or more storeys, with dual framing (stronger lower floor frames) and/or open plan ground floors. These measures mitigate against failure of upper storeys that still may be constructed in timber (although light steel is preferable), but for a lower effective wave height.

Ria coastal areas experience highly destructive tsunamis with greater force and inundation height than coastal plains. For the best chance of survival, only substantial RC or steel-framed structures five or more storeys in height (preferably with open plan ground floors) should be permitted in the coastal zone, with where possible open ground floor construction and strong ground floor columns, and orientated longest side perpendicular to the shoreline. Light framed structures such as small commercial and residential buildings should be located outside the inundation zone.

### Vertical Evacuation Shelters

The purpose of vertical evacuation (VE) shelters is to elevate residents to a place of safety above the tsunami inundation height. According to FEMA P646 Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA, 2008), the design elevation is given by:

$$\text{Design Elevation} = \text{Inundation height} + (30\% \text{ of inundation height})$$

Designated VE shelters are often multi-purpose buildings that serve as a commercial, community or private facility when not acting as a refuge. This is more cost-effective than constructing structures for the sole purpose of acting as a shelter (MacRae, 2011). A number buildings in Ofunato appeared from the survey to be potential multi-purpose VE Shelters (Fig. 12) as they were steel or RC framed, three or more storeys in height with damage level D1. Locations ranged from 65-450m from the shoreline, contrasting with the city's designated shelters, all but one of which were positioned outside the inundation zone indicated by the blue line in  Figure 12.

VE Case Studies - Ofunato

Ofunato Elementary School is a three storey RC structure (Figure 13), located 490m from the shoreline with damage level D0. The school is well positioned on higher ground to serve as a shelter. Schools are commonly designated as VE shelters in Japan because they are built to high seismic standards and have capacity for large numbers of evacuees.

The five-storey steel-framed Maiya Shopping Centre was at the forefront of the tsunami, 100m from the coastline, yet survived with damage level D2 (Figure 14) despite inundation to third floor level (9m). Under FEMA guidelines, it had sufficient height to serve as a shelter. The ground floor is relatively open (serving as a customer car park), allowing water to pass through. This was also the case with an open plan construction car park directly in front of the shopping centre that suffered damage D1.

**Figure 12** Locations of possible multi-purpose VE shelters (shown in red) within inundation zone at Ofunato, superimposed on map of designated VE shelters (in blue) (IIS, 2011)

**Figure 13** Potential VE Shelter: Ofunato Elementary School (GSV, 2013b)

**Figure 14** Potential VE Shelter, Ofunato: Maiya Shopping Centre (GSV, 2013b)

VE Case Studies - Ishinomaki

The tsunami height at the shoreline was approximately 6.5m (EEFIT, 2011), giving a VE shelter design elevation of 11.5m (*i.e*. three or four storeys). There were no designated VE Shelters in the surveyed areas prior to 2011. However, the survey highlighted eight buildings as potential shelters – three schools and five RC residential apartment blocks, all within 200m of the shore and which despite suffering inundation to third floor level were high enough to serve as shelters, as they have four storeys with roof access.

Minati Junior High School is located 750m from the shore and suffered damage D1. The size of the structural columns suggests the school is RC construction (Figure 15). Parts of the ground floor are open plan, used for car parking, and the school has a number of external staircases (possibly fire escape routes) to the uppermost floors that would enable evacuees in the surrounding houses readily to use it as a VE Shelter.

**Figure 15** Potential VE Shelter, Ishinomaki: Minati Junior High School (GSV, 2013c)

VE Shelters - Summary

A cost-effective approach to the provision of Vertical Evacuation Shelters is to designate buildings that already have another function or construct new buildings with a dual purpose to act as a shelter when required. Successful performance of such structures has been demonstrated in the case study zones. Major multi-occupancy buildings such as schools or shopping centres are a good choice for shelters as they are most likely already designed to high seismic standards and therefore have sufficiently strong columns and foundations (particularly if the building has open ground floor construction but yet was still designed to seismic codes), and also tend to have good roof access. Utilising such buildings within an overall urban planning context should enable provision of VE shelters at a range of distances from the shore, giving close proximity to as many people as possible.

**Summary – Redevelopment Models**

Models for planning the redevelopment of coastal communities may be postulated based on the lessons learned from the case studies of Ofunato and Ishinomaki, as shown in Figures 16 and 17. Table 2 gives the key to symbols used in the Figures.

**Figure 16** Coastal Plains redevelopment proposal

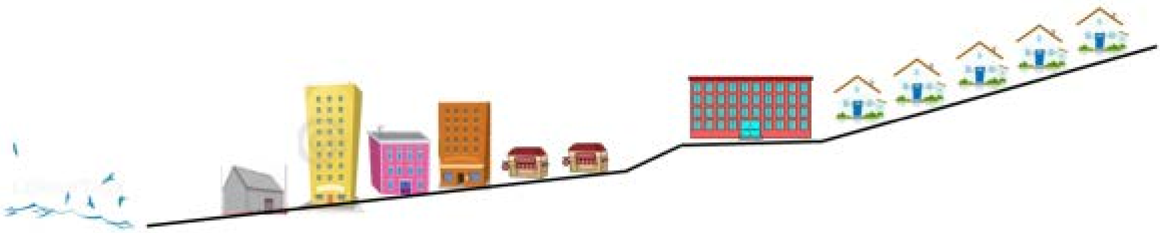
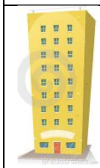
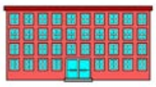


**Figure 17** Rias coastline redevelopment proposal

Table 1 Key to redevelopment proposals in Figures 16 and 17

| **IMAGE** | **DESCRIPTION** |
|---|---|
|  | Industrial buildings |
|  | Row of trees parallel to shoreline |
|  | Purpose built Vertical Evacuation Shelters with open plan ground floor |
|  | Small commercial buildings with open plan ground floor |
|  | Housing with dual frame construction |
|  | Traditional timber construction housing (nominally non-tsunami proof) |
|  Community  Private  Commercial | Multi-purpose Vertical Evacuation Shelters |

## Conclusions

This project has demonstrated the use of an internet portal enabling easy comparison of Google Street View 'Before' and 'After' images to survey damage to buildings in different coastal communities affected by a tsunami. It has drawn conclusions on individual building performance similar to those in other studies such as by EEFIT, but with much less use of resource and with the ability to make connections between different occurrences of particular successful structural forms, for example dual-frame construction, open ground floor and multi-use vertical evacuation shelters. At the level of a district or whole urban area, it has been possible to assess both quantitatively and qualitatively the performances of different structure types as functions of factors such as distance from shoreline and sheltering by trees and other buildings, and also draw conclusions on the selection and positioning of multi-use vertical evacuation shelter structures. These have enabled broad plans for urban redevelopment for tsunami resilience in ria and coastal plain communities to be proposed.

Practical advantages found in using the Google Street View portal are firstly that for individual buildings, it is quick and easy to link damage to location relative to the shoreline and other structures of interest, due to integration of Street View and GPS location data. Secondly, the availability of 'Before' images as well as 'After' makes it possible to quantify at street or zone level the percentage of buildings completely washed away, and gain an impression of their likely structural forms. However, it is not possible to be certain of the structural form and material of a completely collapsed building, and this is where a field visit has the advantage in being able to view the debris. The remote survey tends to concentrate on learning from structures that are still standing to some extent.

Even for buildings partially standing, it is sometimes difficult to remotely assess their structural forms with certainty, particularly for unusual forms such as the structural panel houses observed in this study. This shows the benefit of local knowledge gained from a hands-on field survey or by talking to local engineers and academics (although the latter could be done remotely). Other limitations of the remote data include that it was not possible to assess inundation depths accurately from the 'After' images because watermarks are hard to see, so that reference was made on this point to the EEFIT field study. 'After' images are limited by where a Google Street View car can access, generally not including inside buildings or non-public areas such as industrial complexes or along coastal defences. The lapse of time before the Google Street View cars arrived meant that significant clearing up had taken place, so that an unknown number of buildings partially standing after the event may have been removed. Generally, however, this study has shown the benefit of availability of readily comparable Google Street View images 'Before' and 'After' a major natural disaster to enable researchers and engineers from around the world to share in researching its damaging effects, in collaboration with local experts.

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